

A Feasibility Study of Magneto-Rheological Fluids for Micro Devices

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Abstract of thesis entitled

By using Magnetorheological (MR) fluids, many conventional electromechanical devices and systems have benefited in achieving faster system response, quiet operation, high reliability, and system simplicity. An investigation on applying commercial MR fluids in microelectromechanical systems (MEMS) is in progress and is reported here. Experimental and theoretical studies have been performed on using MR fluids in micron-scale devices. A process technology to integrate a commercial MR fluid with submillimeter systems was investigated. Experimental results indicate that the surface tension of MR fluids will affect their behaviour at the micron scale level significantly. MR fluid pillars on free fluid surfaces were also generated and actuated by varying magnetic field beneath the free surfaces.

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摘要

現時很多傳統的電機裝置和系統都能夠利用磁流變液體得到更大的好處，例如更快速的系統反應，運作時候更寧靜，以及可以簡化系統。在這篇論文中，我們利用一些從市面上購入的磁流變液體，直接應用於微電機系統當中。而將磁流變液體應用於微米裝置的實驗和理論研究已經展開。另外，一種可以把磁流變液體結合於亞毫米系統的製作技術正在研究中。實驗結果指出表面張力對於磁流變液體在微米尺度下的行為有很大影響。將磁流變液體放於磁場下，會使它變成柱狀。

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LIST OF VARIABLES

V_{ER}	: Volume of ER fluid
V_{MR}	: Volume of MR fluid
η_{ER}	: Viscosity of ER fluid
η_{MR}	: Viscosity of MR fluid
τ_{ER}	: Shear stress of ER fluid
τ_{MR}	: Shear stress of MR fluid
V_{min}	: Minimum active volume
$F\tau$: Shear force
$F\eta$: Viscous force
S	: Speed
H_z	: Magnetic field in Z direction
P	: Power
I	: Current
ρ	: Resistivity
l	: Total length of coil
A	: Cross section area of coil

CHAPTER ONE: INTRODUCTION

Introduction

Magnetorheological (MR) fluid as a controllable fluid has been used in many electromechanical devices and systems [1.1]. The controllability of the yield stress in MR fluids under magnetic field allows some electromechanical systems to operate with increasing simplicity, quietness, rapid-response, and high reliability. MR fluids are suspensions of very small magnetic particles in carrier fluid and are free flowing liquids like motor oil if no magnetic field is applied. However, MR fluids are changed from liquid state into a near-solid state under a magnetic field. The degree of force resistance change is proportional to the magnitude of the applied magnetic field [1.2]. By changing the applied magnetic fields, the behaviour of MR fluid in clutches, brakes, dampers, and valves can be controlled to obtain the required dynamic characteristics.

Motivation of the Problem

The successfulness of applying MR fluids in the macro systems motivates us to investigate the feasibility of applying MR fluids in micro systems. Before we apply MR fluids in MEMS, there are few problems we should solve first. Electrorheological (ER) fluid, MR fluid and Ferrofluid, all have similar properties. Why did we choose MR fluid and not Ferrofluid or Electrorheological fluid? Is MR fluid is better than the other fluids, in terms of applying it to micro systems? What are the constraints that we should consider? Moreover, the viscosity of the MR fluid is dependent on the magnetic field strength, so can the existing micro systems generate enough magnetic fields to change the viscosity of the MR fluid? What kind of device and materials can be used to generate the magnetic field and what is the strength of magnetic field can be produced by them? To potentially use

MR fluid in MEMS or millimeter scale systems, a suitable technique to allocate MR fluid to the desired positions on a planar substrate is required. The widely used photolithography technique for MEMS is not suitable for MR fluid and we need to find the other processing techniques that are suitable for integrating MR fluids into micro systems.

Organization of this Thesis

This thesis consists of seven chapters. In chapter 2, we will make a brief description of the Electrorheological fluid, MR fluid and Ferrofluid. In chapter 3, the theoretical analysis of MR fluid in micro scale will be carried out. A process technology for MR fluid in submillimeter scale will be introduced in chapter 4. Chapter 5 describes the behavior of MR fluid pillars in detail. Chapter 6 proposes some possible application for MR fluid in micro systems. Finally, Chapter 7 concludes this thesis.

CHAPTER TWO: LITERATURE SURVEY

Introduction

Controllable fluids are materials that will change their rheological property when the magnetic field or electric field is applied on them. The development of yield stress in the fluid is dependent on the magnitude of the applied field. Typically, these materials are referred to as MR fluids and Electrorheological fluids. By using the controllable fluids, many conventional electromechanical devices and system have benefited in achieving faster system response, quiet operation, high reliability, and system simplicity. In this chapter, we will explain the basic properties of Electrorheological fluids, MR fluids and Ferrofluid. We will also point out the advantages and disadvantages of these fluids. Lastly, we will point out why we chose MR fluid as the controllable fluid for micro systems.

Electrorheological Fluid

Willis Winslow is the first person to identify the potential of the controllable fluid in 1949 and published the first paper that describes the Electrorheological effect [2.1]. Electrorheological fluids consist of dielectric liquid that disperse fine polarizable particles. The dimensions of the particles are typically from $0.1\mu\text{m}$ to $10\mu\text{m}$. Under the application of electric field, the particles will be polarized and arrange themselves into chains across the electrodes. As a result, the viscosity of the Electrorheological fluid will increase. The increase in viscosity is dependent on the magnitude of the applied electric field. When the electric field is below 1KV/mm , the Electrorheological fluid is in an essentially liquid state. However, when the electric field is increased, the fluid will change from liquid

state to solid state and a yield stress will develop inside the fluid. Typically, the rheological property will appear when $\sim 3\text{KV/mm}$ electric field is applied [2.2][2.3].

Magnetorheological Fluid

A MR fluid is suspensions of very small magnetic particles in carrier fluids and is a free flowing liquid like motor oil if no magnetic field is applied. However, MR fluid is changed from liquid state into a near-solid state under a magnetic field. The particles inside the fluid will be polarized and form into chains of particles inside the fluid. As a result, the chains of the particles will increase the viscosity of the fluid and resist the flow of the fluid. When the magnetic field is removed, the particles will return to its free state and the viscosity will also decrease. The decrease of the force resistance change is more or less proportional to the magnitude of the applied magnetic field.

Ferrofluid

Ferrofluid is different from MR and Electrorheological fluids. Ferrofluid are stable dispersions of nanosized superparamagnetic particles ($\sim 5\text{-}10\text{nm}$) of such materials as iron oxide. Under the application of magnetic field, Ferrofluid does not have particle structuring or resist the flow of Ferrofluid. However, the Ferrofluid will experience a body force on the material that is proportional to the magnetic field gradient. This force will make the Ferrofluid to be attracted to the region that has high magnetic field [2.4].

Comparison Amount ER, MR and Ferrofluid

Electrorheological fluid and MR fluid can be used in the devices that require varying damping force or resistance of flow. Although Electrorheological fluid was developed earlier and better known than MR fluid, interest in MR fluid is currently more than Electrorheological fluid, due to several advantages over Electrorheological fluid.

MR fluid can generate higher yield strength than Electrorheological fluid. In general, MR fluid can generate up to 100kpa yield strength while Electrorheological fluid can only generate up to 5kpa. As a result, MR fluid can provide higher damping force and flow of resistance than the Electrorheological fluid device.

The particle chains inside the Electrorheological fluid is generated by the high electric field that is typically up to 3kV/mm. The high voltage power supply is very expensive. The magnetic field that is required by the Magnetorheological fluid can be generated by the permanent magnet or electromagnetic coil that only require low voltage supply to operate it.

The maximum yield strength that can be generated by the MR fluid is constrained by the particles inside it. After a certain value of magnetic field, the particle will become saturated. The increase of magnetic field will not increase the attractive force between each particle and the yield strength will become constant. In the case of Electrorheological fluid, the maximum yield strength is constrained by the carrier fluid. If the electric field is larger than certain value, the high electric field will breakdown the fluid. Short circuit will occur and it is very dangerous due to the high voltage difference.

Minimal volume requirement is one of the constraints that we shall consider. This is the amount of fluid that must be used for the controllable fluid to

be effective. This constraint is explained in chapter three, "Theoretical analysis of MR fluid in MEMS". Ferrofluid does not develop a yield stress on application of magnetic field. Our current interest is in investigating fluids in micro systems that will vary yield stress according to applied field strength, so we did not compare it to the other fluids. The working region of the device is dependent on the ratio (η/τ^2) , (η is the viscosity, τ is the shear stress), so we can compare the relative effectiveness of the MR fluid and Electrorheological fluid to achieve comparable device performance. By assume the same control ratio, speed and force, we can obtain the relation (Eq. 2.1)[1.1]

$$\frac{V_{ER}}{V_{MR}} = \frac{\eta_{ER} / \tau_{ER}^2}{\eta_{MR} / \tau_{MR}^2} \quad (2.1)$$

By simplifying Equation 2.1, we will obtain Equation 2.2:

$$\frac{V_{ER}}{V_{MR}} = \left(\frac{\tau_{MR}}{\tau_{ER}} \right)^2 \quad (2.2)$$

The yield strength that can be generated by Electrorheological fluid is ~3-5kPa and MR fluid is ~20-100kPa. The volume ratio is about 4-30. It means that MR fluid device can be much smaller than the Electrorheological fluid device with similar performance [1.1].

MR fluid is also more attractive due to the high yield strength that can produce. The comparison amount MR fluid, Electrorheological fluid and Ferrofluid can be found in Table 1. [2.3]

	MR Fluid	ER Fluid	Ferrofluid
Particulate Material	Iron	Polymers, Ceramics	Ferrites
Particle Size	0.1-10 μ m	0.1 μ m-10 μ m	2-10nm
Suspending Fluid	Polar Liquids	Oils	Oils, water
Density (g/cm ³)	3-5	1-2	1-2
Off Viscosity (mPa s)	100-1000	50-1000	2-500
Required Field	~3kOe	~3kV/mm	~1kOe
Field-Induced Changes	$\tau_y(B) \sim 100\text{kPa}$	$\tau_y(E) \sim 5\text{kPa}$	$\Delta\eta(B)/\eta(0) \sim 2$
Device Excitation	Electromagnets, Permanent magnets	High Voltage	Permanent magnets

Table 1. Representative composition and properties of MR fluid, Electrorheological fluid and Ferrofluid.

CHAPTER THREE:

THEORETICAL ANALYSIS OF MR FLUIDS FOR MICRO DEVICES

Introduction

MR fluid as a controllable fluid has been used in many electromechanical device and systems [2.2] and have already been studied extensively in macro scale level [3.1]. However, the applications of MR fluid in micro devices or systems have not been studied. In this chapter, we will discuss some of the basic requirements to use MR fluid in micro systems. What is minimal active fluid volume that is necessary to achieve the system requirement? What is the magnetic fields strength that can be generated by typical micro-coils? Power consumption of the micro-coil? What is the relation between the yield strength that can be generated by the MR fluid with different strength of magnetic field? How the dimension of the particles will affect the size of the micro devices?

Minimal Volume

There are three working modes in MR fluid devices: shear mode, flow mode, and squeeze mode [3.2]. In shear mode, MR fluid is placed between a fixed and moving surface with the magnetic field perpendicular to the motion of the moving surface, such as in MR fluid clutches (Figure 3.1). In flow mode, MR fluid flows directly between two fixed surfaces with the magnetic field perpendicular to the motion of the fluid. This is the working mode for valves and dampers (Figure 3.2). In squeeze mode, MR fluid is squeezed in normal direction and flows in shear direction. This mode is for dampers that require high stiffness (Figure 3.3).

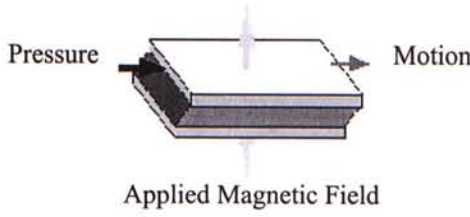


Figure 3.1 Shear mode

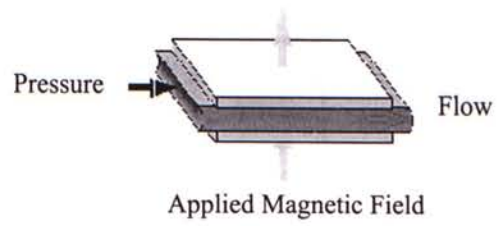


Figure 3.2 Flow mode

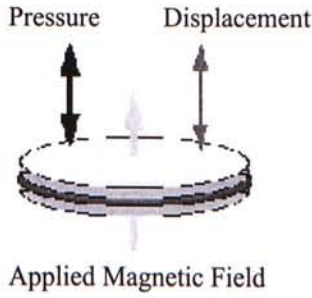


Figure 3.3 Squeeze mode

The resistant force in shear mode is divided into field independent viscous force F_η and an induced shear force F_τ . A minimal active fluid volume V_{min} is required as follow (Eq. 3.1)(this amount of fluid must be used for the MR fluid to be effective) [2.1]

$$V_{min} = \left(\frac{\eta}{\tau^2} \right) \left(\frac{F_\tau}{F_\eta} \right) F_\tau S \quad (3.1)$$

Where η is the viscosity without magnetic field, τ is the yield stress developed in response to applied magnetic field and S is the speed of the movable surface. The control ratio (F_τ/F_η) , shear force F_τ and speed S are determined by the application. Typically, the viscosity of MR fluid is about 0.25 Pa-s at 25 °C. We assume the minimal requirements for F_τ and S are 1mN and 1 mm/s, respectively, for MEMS application. The calculated minimal volumes to meet the requirements are illustrated in (Figure 3.4).

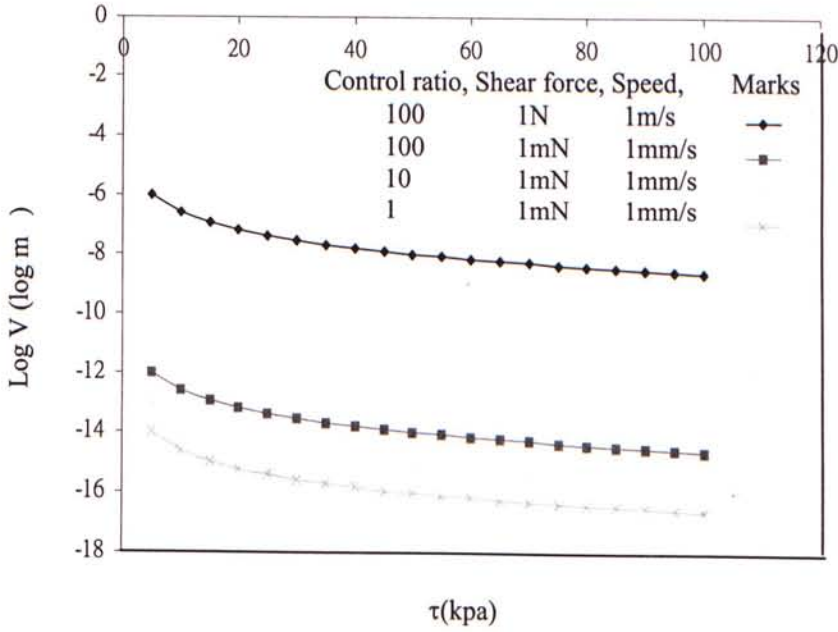


Figure 3.4 The minimal volumes to meet the requirements

As shown in Figure 3.4, the minimal volumes for MEMS requirements are located in the range from 10^{-12} to 10^{-16} m^3 . This indicated that to use MR fluid in MEMS applications the device linear dimensions should be at least $\sim 10\mu\text{m}$ (10^{-5} m).

Magnetic Field Requirement

The viscosity of the MR fluid is dependent on the magnitude of the magnetic field around it. Planar coils (Figure 3.5) are most suitable for generating magnetic field in micro systems since they are compatible with MEMS/IC techniques. The fabrication techniques of planar coils have been well developed. Changing the current supplied to the coils can control the magnitude of the magnetic field. The magnetic field produced by one planar coil in the z direction can be calculated by the following equation (Eq. 3.2) [3.3]:

$$H_z = \frac{1}{4\pi} \left[\frac{a_1}{a_1^2 + z^2} \left(\frac{b_1}{r_1} + \frac{b_2}{r_2} \right) + \frac{a_2}{a_2^2 + z^2} \left(\frac{b_1}{r_3} + \frac{b_2}{r_4} \right) \right] + \frac{b_1}{b_1^2 + z^2} \left(\frac{a_1}{r_1} + \frac{a_2}{r_3} \right) + \frac{b_2}{b_2^2 + z^2} \left(\frac{a_1}{r_2} + \frac{a_2}{r_4} \right) \quad (3.2)$$

The definition of each variable in Equation 3.2 is given in Figure 3.6. The magnetic field at the center of multiple loops of coils was tabulated using the above equation and the results are shown in Figure 3.7. To minimize the resistance of the coil, copper ($1.7 \times 10^{-8} \Omega\text{m}$) is chosen as the coil material for the analysis. We assumed the width of the coil is $30\mu\text{m}$ and the distance between each coil is $20\mu\text{m}$. The dimensions of the substrate for the coils are $5\text{mm} \times 5\text{mm}$. The power required by the planar coils can be calculated by the following equation (Eq. 3.3):

$$P = I^2 \frac{\rho l}{A} \quad (3.3)$$

In the above equation, ρ , l and A are the resistivity, the total length and the cross section area of the coil, respectively.

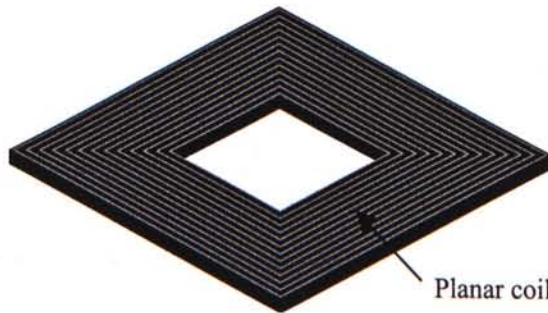


Figure 3.5 Rectangular coil

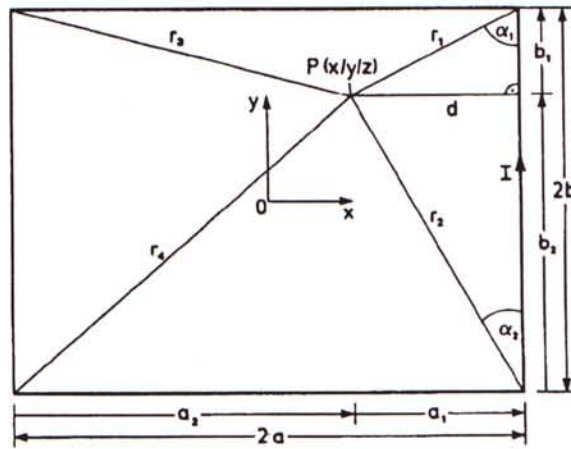


Figure 3.6 Parameters for calculating the magnetic field at a point (x, y, z) for a rectangular coil [3.3]

The power requirement is shown in Figure 3.8. This figure indicates that to be compatible with current MEMS systems, which typically have maximum power output of 1 Watt, only ~ 50 turns of coil with 50mA of current are allowed. This analysis also shows that the upper limit for generating magnetic field strength with current MEMS compatible technology is in the order of 1kA/m. The manufacturer's data sheet for the MR fluid shear stress versus shear strain rate relationship is shown in Figure 3.9 for several levels of applied magnetic field. As it indicates, for conventional applications the magnetic field strength requirement is at least an order of magnitude higher than that achievable by MEMS planar coils. Typically required field strength is above 80kA/m. In addition, there is too little data for micro compartment. So no conclusion can be made on the shear stress resistance for field strength in the order of versus field strength relationship in this region. There are reported efforts in reducing the required field strength to achieve a certain shear stress resistance, e.g., using nano-magnetic particles [3.2], [3.4]. However, no commercial nano-MR fluid was available at the time of this study.

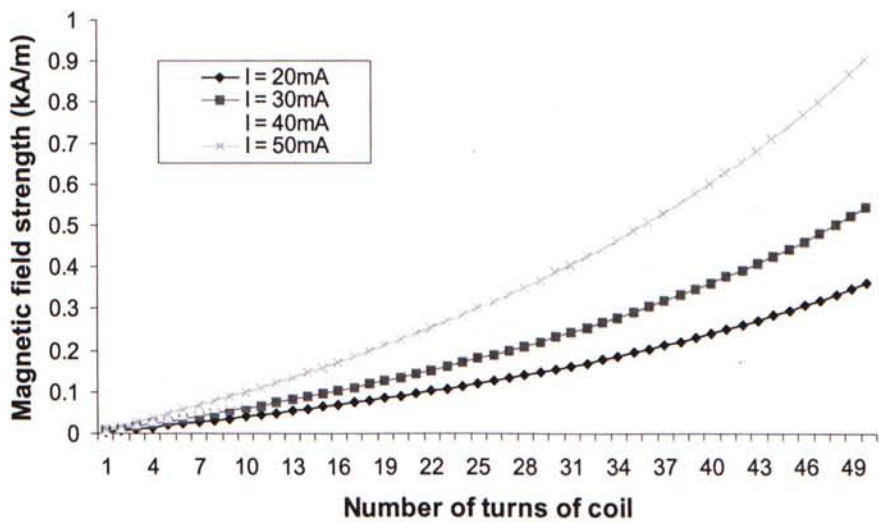


Figure 3.7 The magnitude of the magnetic field versus number of loops of the coils.

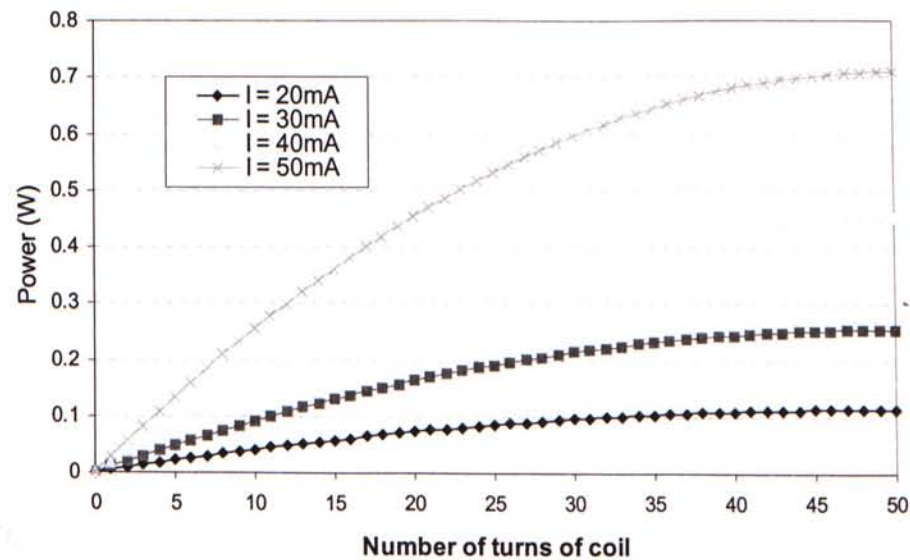


Figure 3.8 Power requirement to generate magnetic field with planar coils on a 5mm*5mm substrate.

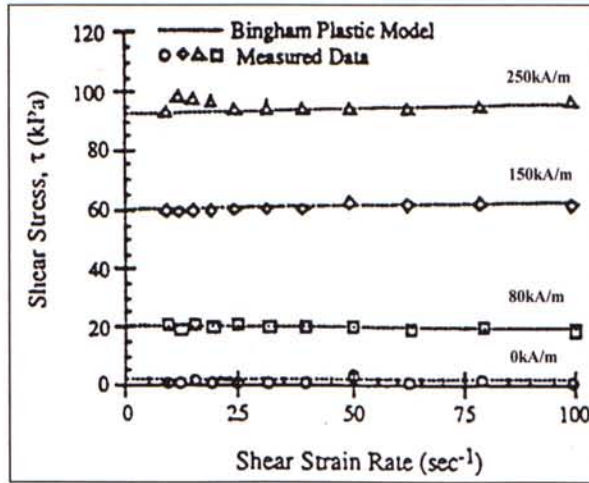


Figure 3.9 Shear stress versus magnetic field strength

(Ref: <http://www.rheologic.com/mrf132ld.html>)

Particle Size

The conventional MR fluids are suspensions of micron-sized magnetizable particles in mineral or silicon oil. The diameter of the magnetizable particles is about several micrometers ($1\sim 3\mu\text{m}$). Since the components of MEMS are also in micron scale, the size of the particles can be a limitation in using MR fluid on some MEMS devices, e.g., micro-channels. Moreover, problems such as sedimentation and abrasion of the particles will further complicate the application of MR fluid in MEMS. Nevertheless, as mentioned previously, MR fluid with nano-sized magnetic particles ($\sim 0.01\mu\text{m}$) as reported in [3.4] may also be used to solve these problems.

CHAPTER FOUR:

PROCESSING TECHNOLOGY

Introduction

As we know, MR fluid has been used in the macro systems. The processing technology for MR fluid in macro systems is available. But how about the micro systems? There are no known techniques to allocate MR fluid into micro systems. In this chapter, we will propose a fabrication method for MR fluids.

Processing Technology

To potentially use MR fluids in MEMS or millimeter scale systems, a suitable technique to allocate MR fluids to the desired positions on a planar substrate is required. MR fluid is a liquid-like material if no magnetic field is applied, so the widely used photolithography technique for MEMS cannot be used. We have examined the screen printing process, which is used in thick film patterning technologies since the inks used for thick film printing are also liquid-like.

The process of screen printing patterns was used by the Egyptians thousands of years ago, and was introduced by IBM as a thick film processing technique in the 60's [4.1], [4.2]. The concept of screen printing is simple. A screen mask with open and closed areas defining the pattern is brought in contact with the surface where the thick film is to be deposited. Fluid ink is forced through the openings in the screen using a squeegee. When the screen is removed, the ink pattern remained.

Our experiments showed that MR fluid can also be “printed” in this way. If a patterned screen is pre-aligned to the pre-fabricated micro cavities, a MR fluid can be allocated to the corresponding cavities (Figure 4.1)

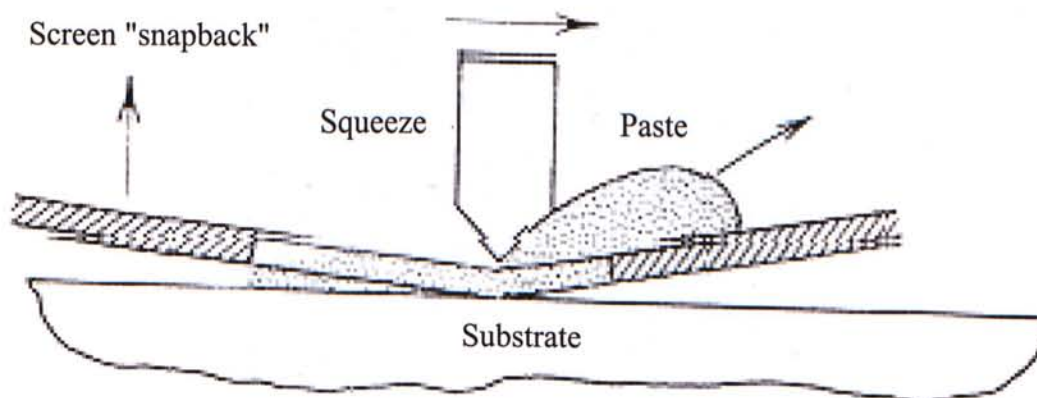


Figure 4.1 Screen printing on Micro cavity [4.1]

A sample of a patterned MR fluid from our experiment is shown in Figure 4.2. The patterned lines shown are $500\mu\text{m}$ in width with $500\mu\text{m}$ gaps. The deposited thickness is about $30\mu\text{m}$ on a flat silicon substrate. Screen printing will play an important role if MR fluid is to be used in MEMS. Currently, from our experiments, the minimal size of MR fluid is limited to about $100\mu\text{m}$ by our screen printing process.

MR fluids must be packaged to prevent evaporation since they are water or oil based fluids. For the same reason, the packaging process must be kept at room temperature. This may be accomplished by using glues or wafer bonding at room temperature.

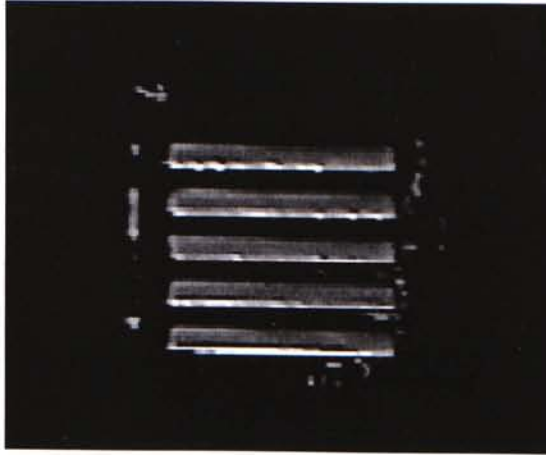


Figure 4.2 MR fluid strips printed on a silicon surface. The strips are $500\mu\text{m}$ wide and 4.5mm long at $500\mu\text{m}$ gaps.

CHAPTER FIVE:

MR FLUID PILLARS

Introduction

MR fluids have been used in many electromechanical devices. Besides the controllable viscosity, are there any other applications for MR fluids? We have found that pillars were generated when we apply magnetic induction on the MR fluid which does not have anything covering it. Moreover, the pillars can lift up some small objects to 1-2mm height. Hence, we can use MR fluids as a meso scale actuator. In this chapter, we will discuss some of the basic phenomenon of the MR fluid pillars. Some experiments have been done to observe the behaviour of MR fluid on free surface. We have also used ANSYS to simulate our experimental environment. By applying different strengths of magnetic induction, the height and size of the pillars will be changed. The pillars' size and height also affected by the surface tension, which was validated by using the iron power to carry out the same experiment.

Description of Experimental Setup

The aim of the experiment is to show the relationship between the strength of magnetic field and the pillars generation. The equipments that we used include a microscope (The Micromanipulator Co. Inc. Model No. 6100) with X, Y and Z tables (Parker Model No. 4504M) (Figure 5.1).

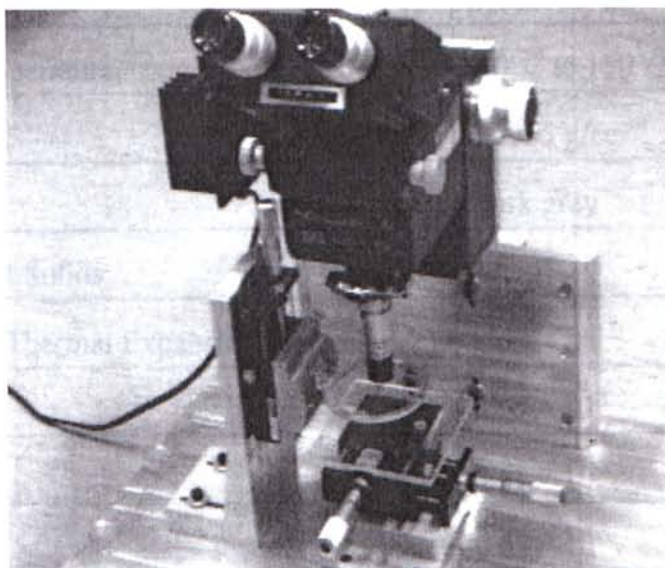


Figure 5.1 The microscope and the X, Y and Z tables

The X and Y tables are fixed together and the magnet is placed on the top of the tables so that we can adjust the position of the magnet in the X and Y directions with the same height. The MR fluid is placed on the plate of the Z table that can be used to adjust the distance between the magnet and the MR fluid. As a result, the strength of the magnet can be adjusted easily.

In addition to these equipments, we have also used a CCD camera (PULNIX TMC-76) to capture the picture of the MR fluid pillars. The camera can also be connected to the microscope to capture the picture of MR fluid pillars from top view.

The MR fluid that we used is a commercial product bought from LORD Corporation, (MRF-132LD). The following is the properties of the MR fluid that we used for the experiment. The following information are duplicated from the product bulletin of MRF-132LD. (Table 2, Figure 5.2, 5.3, 5.4)

Properties	Value/Limits
Fluid	Synthetic Oil
Operating Temperature	-40°C to 150°C
Density	3.0055 g/cc
Color	Dark gray
Weight Percent Solids	80.74%
Coefficient of Thermal Expansion (volume, 1/c)	Units
0 to 50°C	0.55×10^{-3}
50 to 100°C	0.61×10^{-3}
100 to 150°C	0.67×10^{-3}
Specific Heat @ 25°C	0.80 J/g*°C
Thermal Conductivity **25°C	0.25 - 1.06 w/m*°C
Flash point	>150°C
Viscosity 10 s ⁻¹	0.94
Viscosity 80 s ⁻¹	0.33

Table 2. Properties of MR fluid MRF-132LD

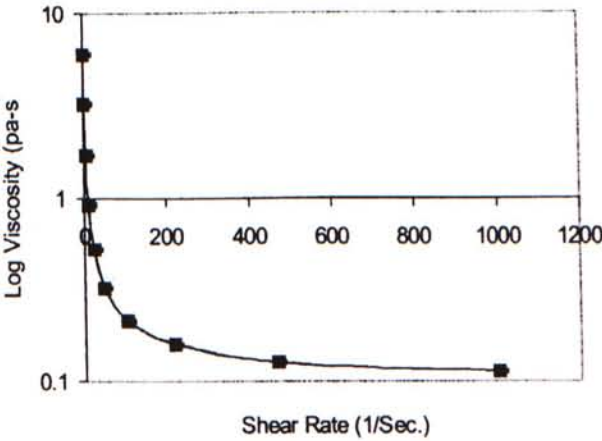


Figure 5.2 Plastic Viscosity as a function of shear rate with no magnetic field

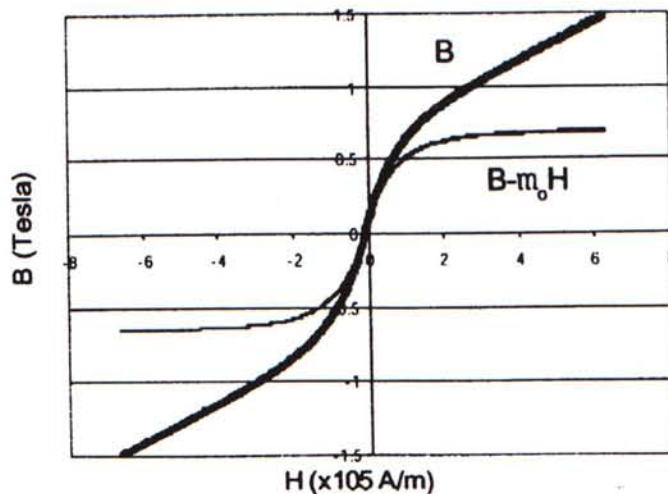


Figure 5.3 Typical magnetic properties of the oil based fluid

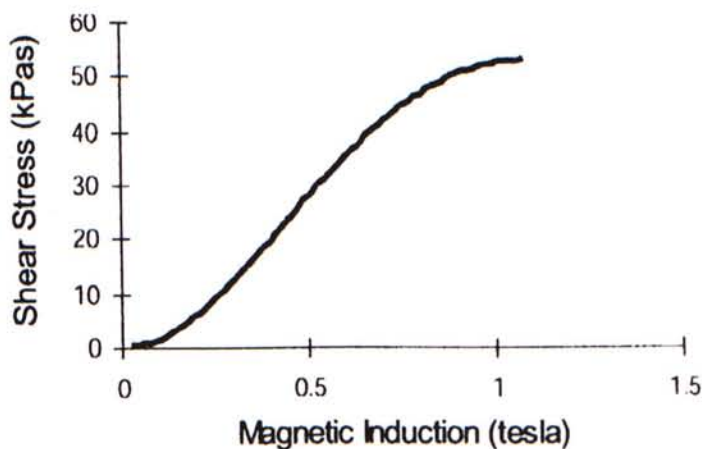


Figure 5.4 Shear stress versus magnetic induction

The magnet that we used was supplied by the Magtech Industrial Company. It is a N40 grade Neodymium Rare Earth permanent magnet. The magnet is cylindrical shape and the dimension is 20mm diameter and 5mm thick. The specifications and a picture of the magnet are shown in Table 3, Figure 5.5 and Figure 5.6.

Residual Flux Density (Br)	13.08kGs
Coercive Force (Hcb)	12.11kOe
Intrinsic Coercive Force (Hcj)	12.75kOe
Max Energy Products (BH)m	39.85MGOe

Table 3. Specification of the magnet

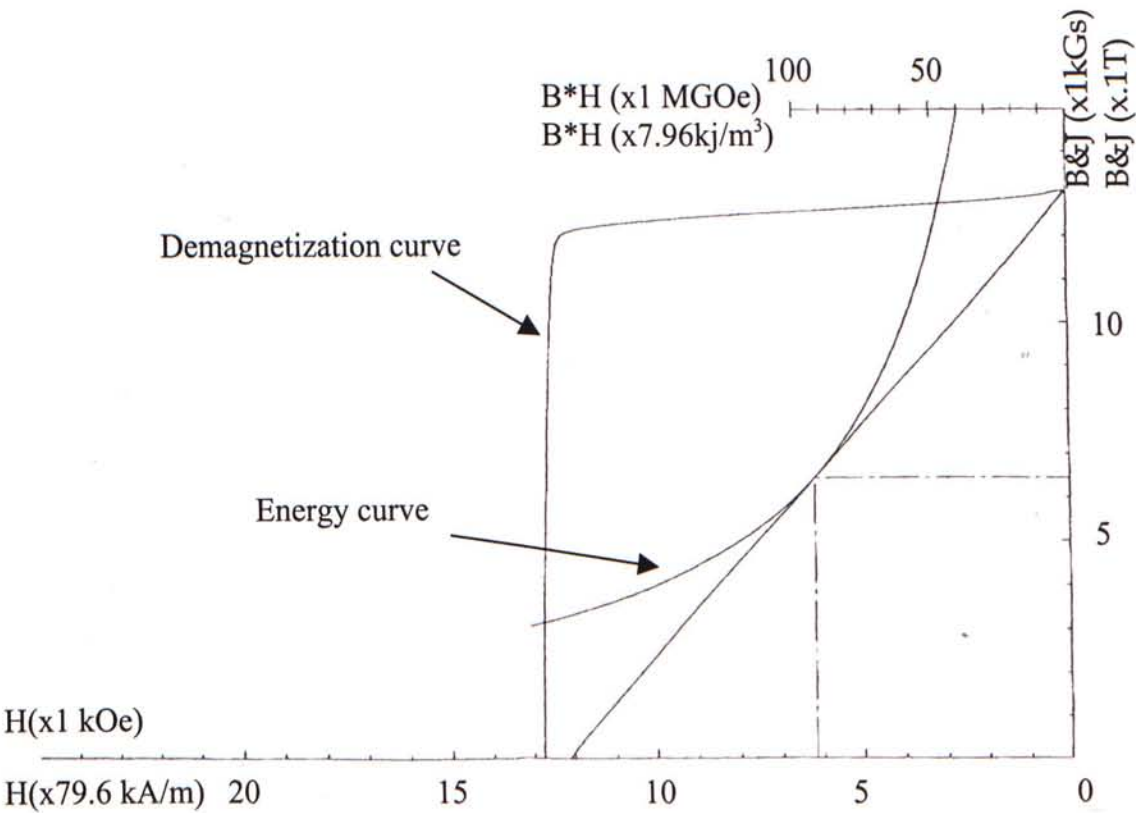


Figure 5.5 Properties of the magnet



Figure 5.6 N40 grade cylinder magnet with 20mm diameter and 5mm thick

Finite element Analysis of the Experiment

We have chosen the software ANSYS to simulate the magnetic flux that can be generated by the magnet in an ideal case. By comparing the difference between the real case and the simulated case, we can show the accuracy of the experiment (Figure 5.7 & Figure 5.8)

In the simulation, we have defined two objects: air and magnet. For any material, ANSYS requires two information: relative permeability (compare to air) or the demagnetization curve (B-H curve) and coercive force. The relative permeability of air is 1 ($4\pi \cdot 10^{-7} \text{ Hm}^{-1}$) and the coercive force is 0. The demagnetization curve of the magnet is shown in Figure 5.5 and the coercive force is 12.11kOe (963.956kA/m). On the right side of Figure 5.7, the information for the simulation is given. SMX is the maximum magnetic induction (Tesla) and SMN is the minimum magnetic induction (Tesla). Different colours represent different strength of magnetic induction and the unit is in Tesla. For Figure 5.8, the strength of magnetic induction and the direction of the potential vectors are shown. The magnet is placed at the center of air space. The size for the air space is 20cm*20cm. (The boundary of the simulation). No magnetic fields are present outside the air space. The rectangular object at the center is the magnet's cross-section. From the simulation, we have found that the magnetic induction (B) near

the surface of the magnet is about 0.24 - 0.29 Tesla. And the magnetic induction is much higher at the edge of the magnet. This explains that why there has more pillars near the edge of the magnet (Figure 5.20, 5.22). From the experiment, we also found that the maximum magnetic induction is about 0.25 Tesla (2.5kGauss) which is measured at the edge of the magnet. The magnetic induction at the center of the surface is about 0.21 Tesla and the simulation result is about 0.19 - 0.24 Tesla. Figure 5.13 & 5.14 are the simulation result of the magnetic field generated by the magnet.

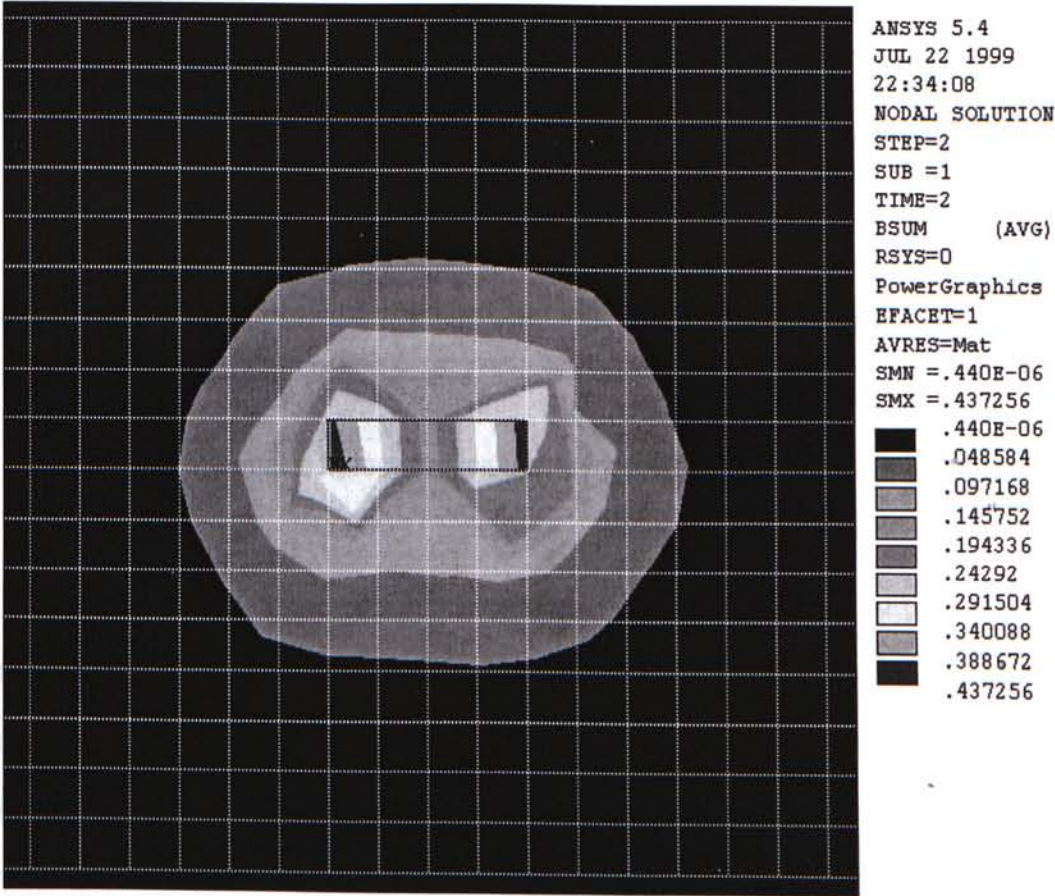


Figure 5.7 The magnetic induction generated by the magnet (nodal solution)

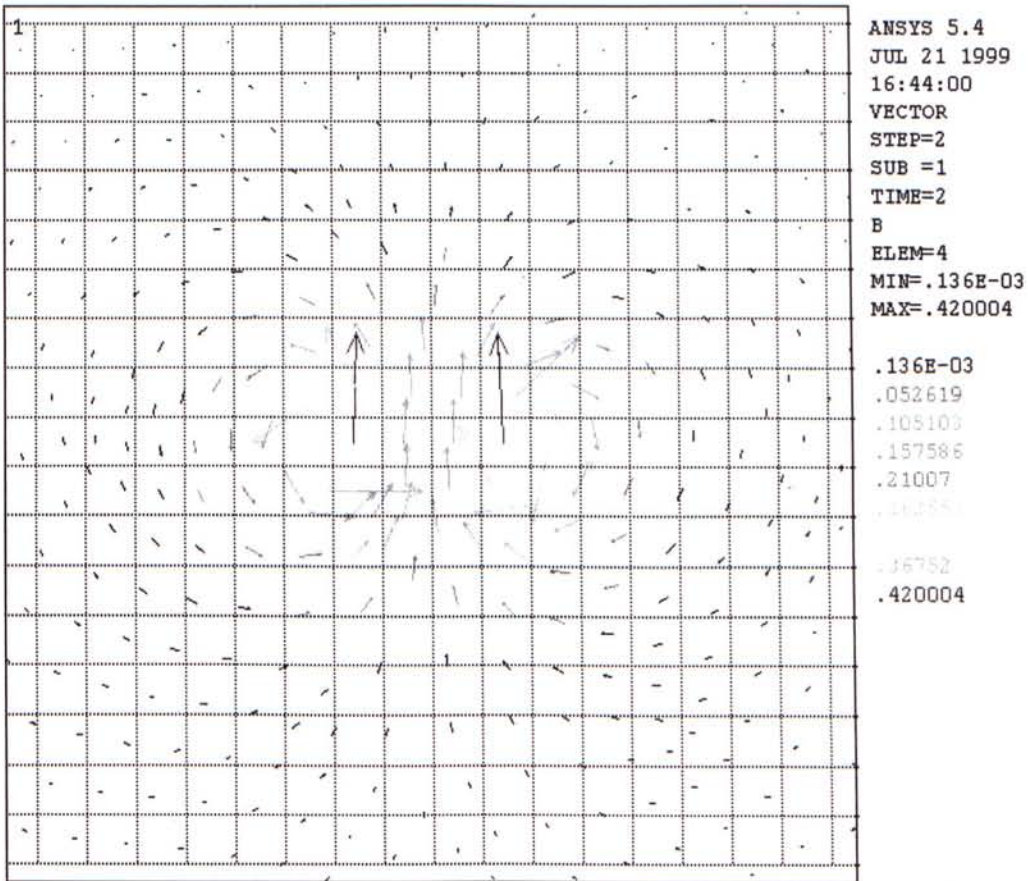


Figure 5.8 The magnetic induction generated by the magnet (vector solution)

Figure 5.9 is the coordinate system of the magnet. Figure 5.10 is the magnetic induction on the surface of the magnet (top) that is measured from the magnet (2D). Figure 5.11 are the magnetic induction of the magnet with different distance (Z direction) from the magnet. Figure 5.12 is the simulation result of the magnetic induction in Z direction.

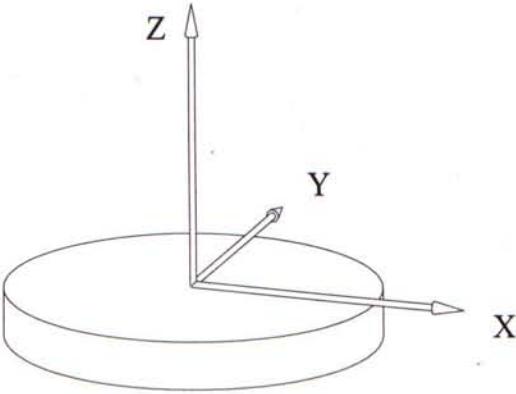


Figure 5.9 The coordinate system of the magnet

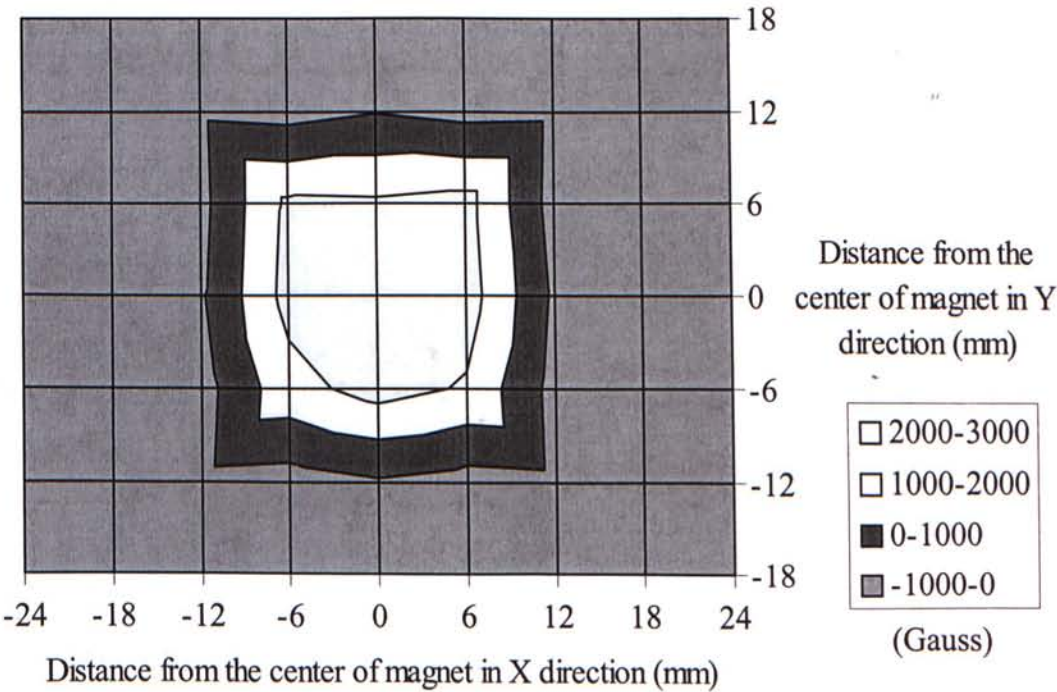


Figure 5.10 Measured magnetic induction on the surface of magnet

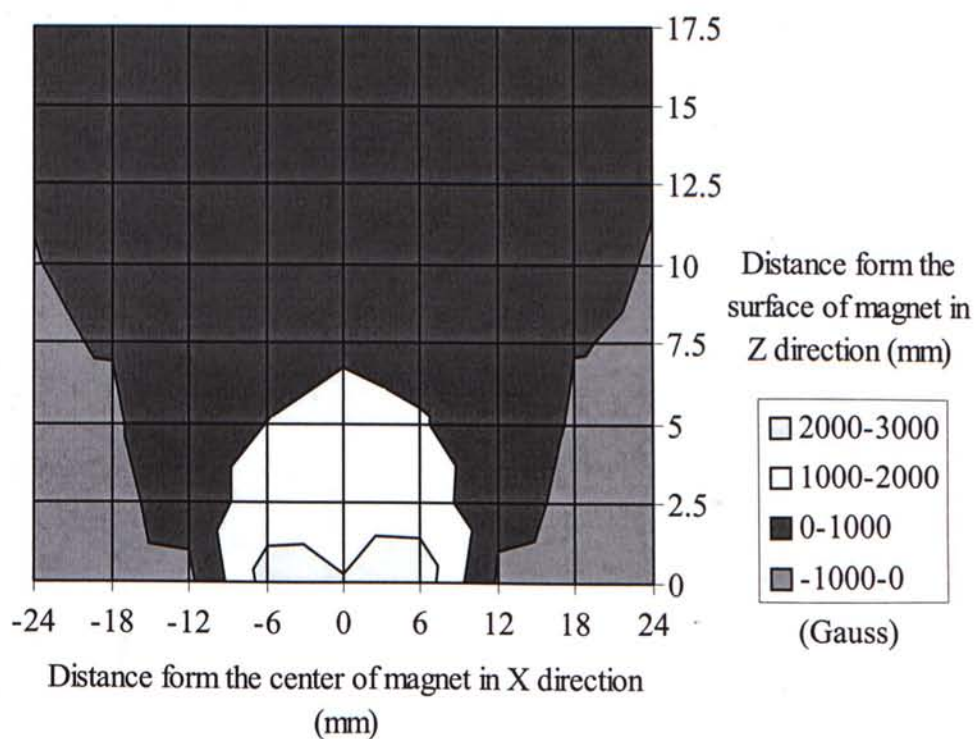


Figure 5.11 The magnetic induction in the z direction with different distance from the magnet

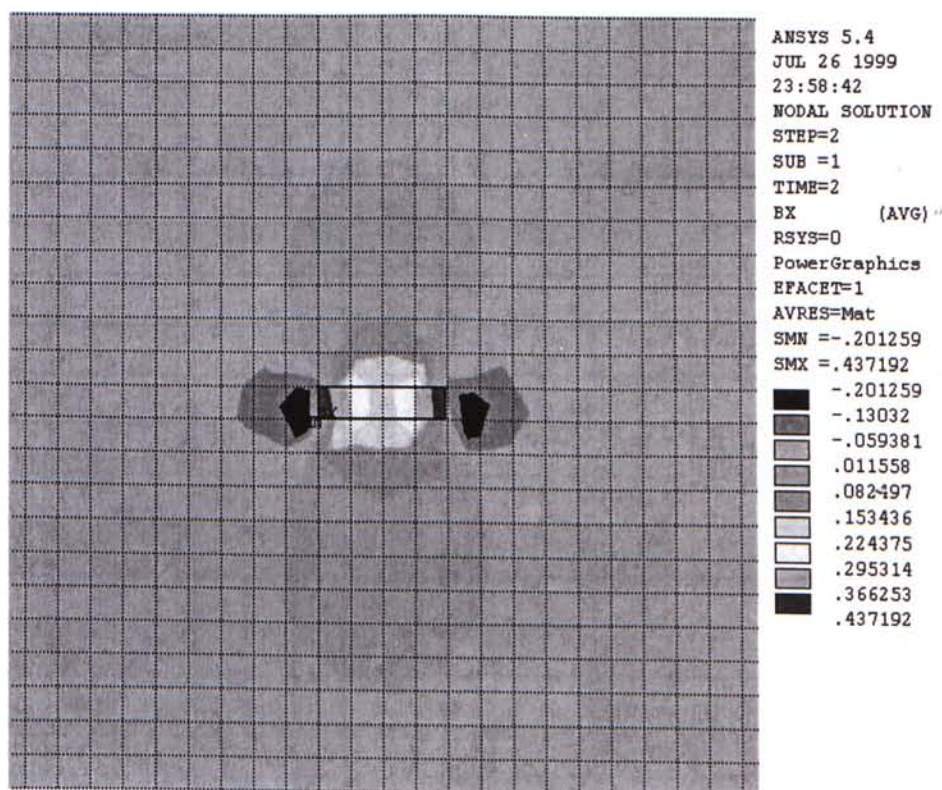


Figure 5.12 Simulated magnetic induction (Tesla) in the Z direction

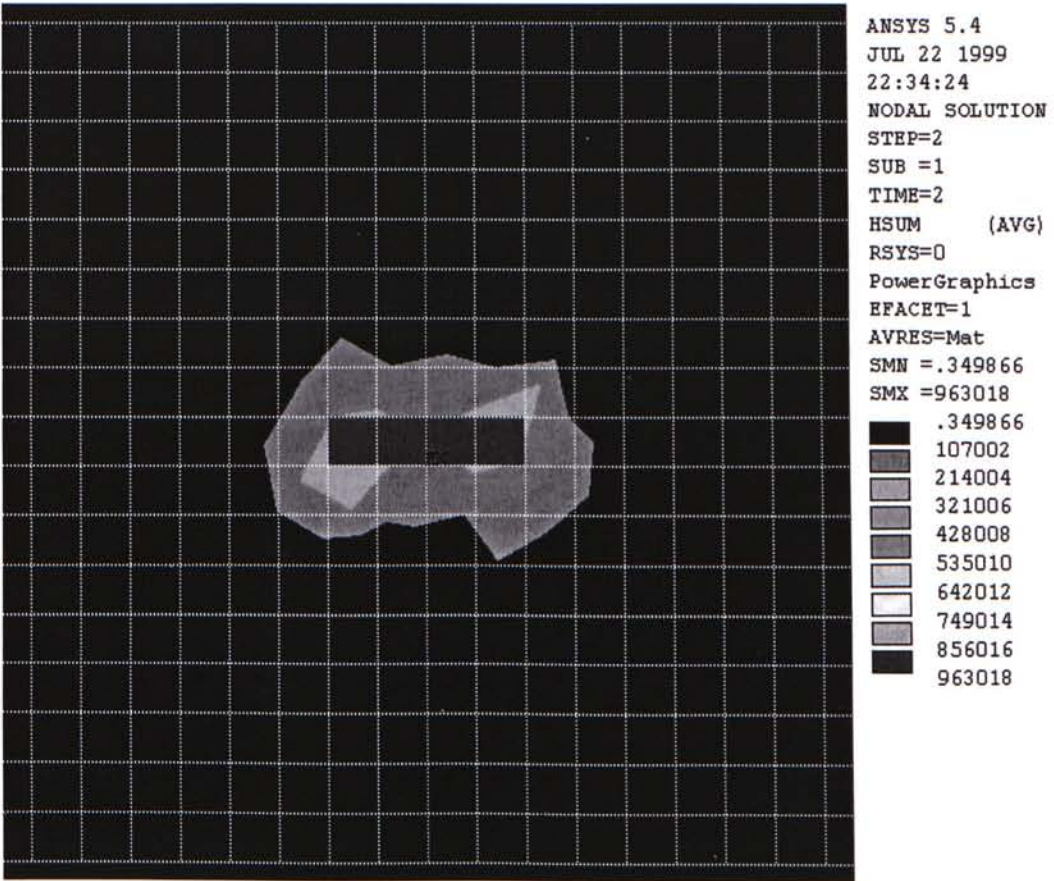


Figure 5.13 The magnetic field (A/m) generated by the magnet (nodal solution)

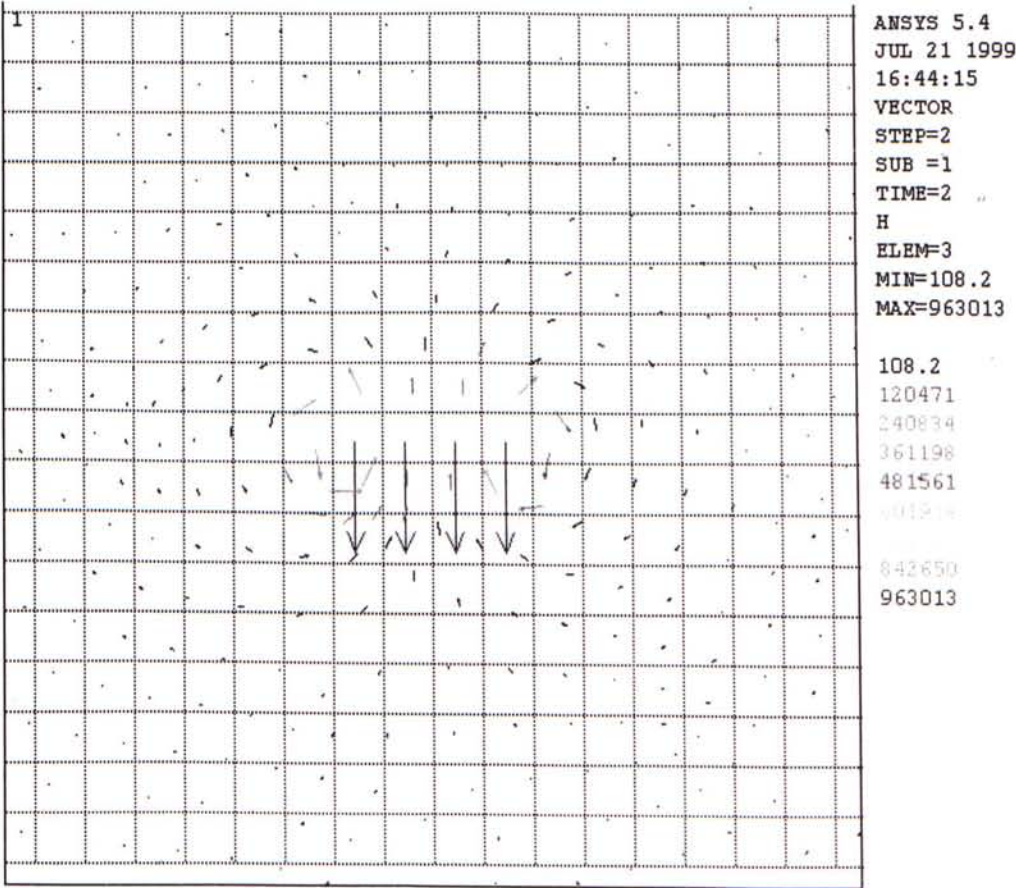


Figure 5.14 The magnetic field (A/m) generated by the magnet (vector solution)

The setting is the same as before. From this simulation, we can find that the magnetic field in the whole magnet is the same (963018 A/m) which is very similar to the coercive force. The value of coercive force indicates the strength of a magnetic field, which demagnetizes a magnet to a non-magnetic status, i.e. the initial magnetic field strength that is stored in the magnet.

Alignment Theory of MR Fluid Pillar

MR fluid pillars are typically like an inverted cone. The pillars will only appear when the magnetic field is high enough. As indicated by Figure 5.15, no pillars can be generated if the field strength is not high enough. The magnetic induction (B) in this case is about 300 Gauss.



Figure 5.15 A drop of MR fluid with 300 Gauss magnetic induction

In Figure 5.16, small pillars were generated on the top of a drop of MR fluid. We can adjust the magnetic induction by adjusting the distance between the magnet and MR fluid. The magnetic induction (B) in this case is about 400 Gauss.



Figure 5.16 Small MR fluid pillars with 400 Gauss magnetic induction

Several flake-like MR fluid pillars appeared when the magnetic induction keeps on increase (Figure 5.17). The magnetic induction (B) in this case is about 500 Gauss.



Figure 5.17 Flake like MR fluid pillars with 500 Gauss magnetic induction

The flake-like pillars divided into thinner pillars when we keep on increasing the magnetic induction. At this time the height of the pillars seem to be shorter than the flake like pillar (Figure 5.18)



Figure 5.18 MR fluid pillars with 1100 Gauss magnetic induction

As the magnetic induction increase to 1900 Gauss. The number of pillar will keep on to increase, moreover, the height and size will decrease (Figure 5.19).

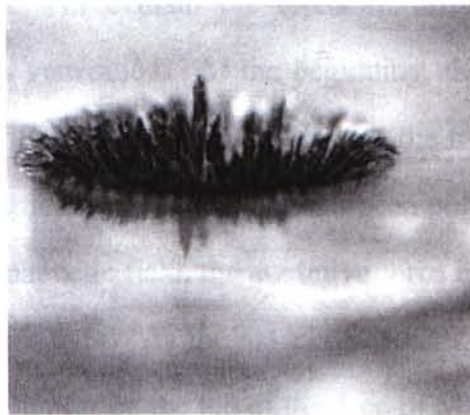


Figure 5.19 MR fluid pillars with 1900 Gauss magnetic induction

At last, when the magnetic induction is adjusted to the maximum value (which is dependent on the magnet), a large numbers of small MR fluid pillars will be observed. At this time, the pillars seemed to be thinner and shorter than the pillars with smaller magnetic induction (Figure 5.20). The magnetic induction (B) in this case is about 2100Gauss.

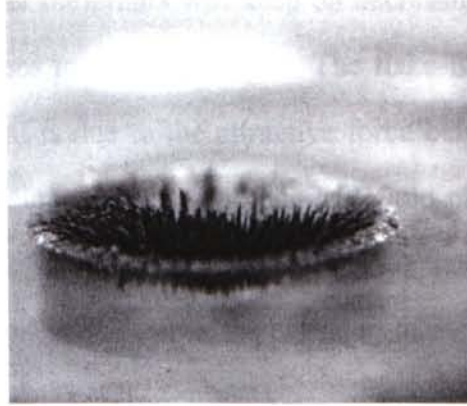


Figure 5.20 MR fluid pillars with 2100 Gauss magnetic induction

From 0 Gauss to 2100 Gauss, we have recorded the variation of the height and shape of MR fluid pillars. These variations are dependent on two factors, the strength of magnetic induction and the surface tension.

In this part, we will explain the effect of different strength magnetic induction on the pillars generation. At the beginning, the magnetic induction is about 300 Gauss, no pillars were generated because the magnetic induction is too small. Although the particles inside the fluid has been polarized and want to align as the direction of the magnetic field, the attractive force between each particle are too small to lift up themselves. As the magnetic induction increased to a certain value, few small pillars appear on the top of the drop of MR fluid. It is because the magnetic force induced in each particle is large enough to lift up the particles. But the force is just enough to lift up few particles, so small pillars appear on the top of fluid.

Flake-like pillars appear when the magnetic induction was increased to 400 Gauss. This effect is mainly due to the surface tension. We will explain this in next part (Discussion of Fluid Surface Tension). When we keep on increasing the magnetic induction, several large flake-like pillars will become higher and larger. And then they will break down into many small pillars, which are much shorter and

smaller in shape. Moreover the pillars will keep on decreasing their size until the magnetic induction increases to a certain value. The flake-like pillar break down into many small pillars that is due to the attractive force between each particle is larger than the surface tension. At this time, the MR fluid pillars are just like the pillars generated by iron powder. The effect due to surface tension can be neglected. The MR fluid pillar aligned as the direction of magnetic field as shown in Figure 5.21.



Figure 5.21 MR fluid pillars aligned as the direction of magnetic field

We have observed that the pillars on the top of the edge of magnet are seemed to be the form of a curve. The pillars also concentrate on the edge of the magnet (Figure 5.22). The alignment of the pillar is just like the direction of magnetic field that was similar to the simulation result from ANSYS. (Figure 5.23)

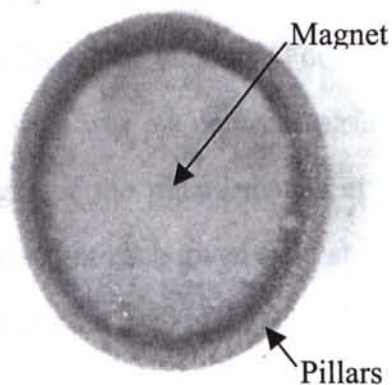


Figure 5.22 Top view of MR fluid pillars

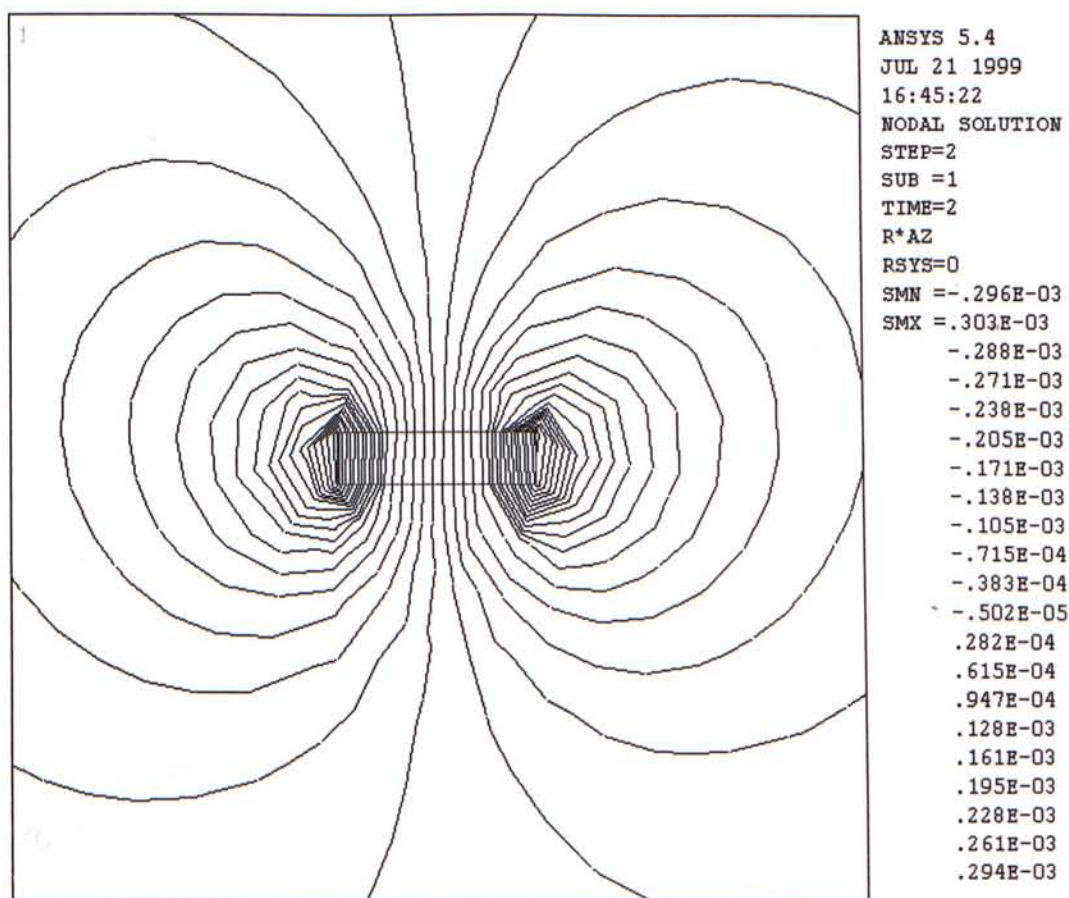


Figure 5.23 The simulation of magnetic flux generated by a magnet

By measuring the pillar heights with different strengths of magnetic induction, Figure 5.24 can be obtained. For each value of the strength of magnetic induction, the MR fluid was put on a flat surface. The pillars lift up, and then we measured the height of the pillars that is at the center of the magnet. Twenty samples were obtained at each given field strength. The average heights of these twenty samples are plotted in Figure 5.24.

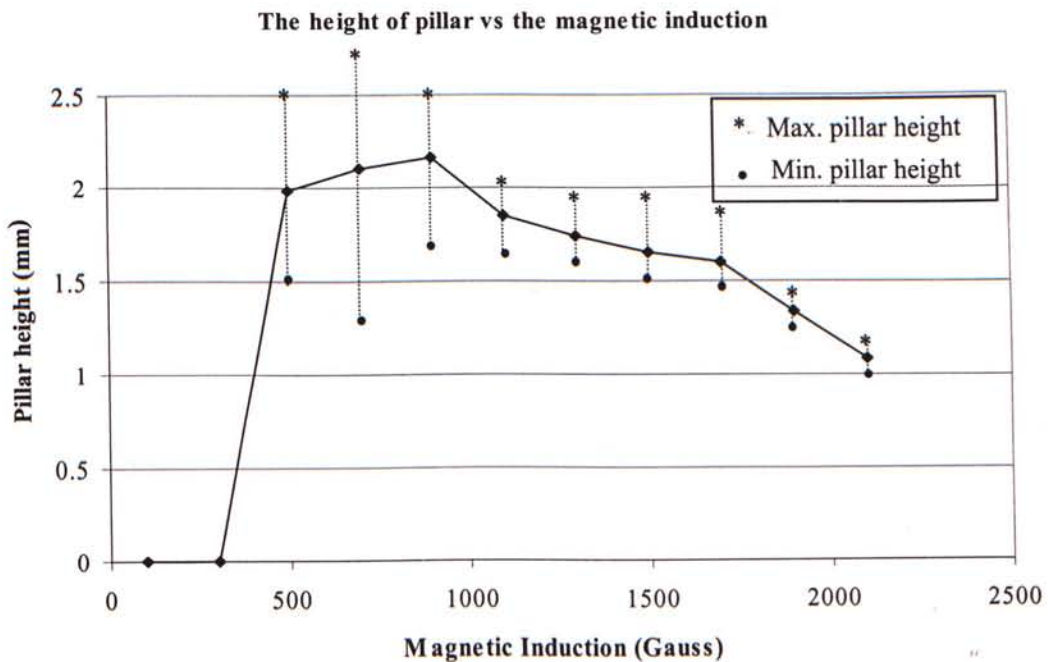


Figure 5.24 The height of pillars versus different strengths magnetic induction

From Figure 5.24, we found that although the strength of magnetic induction was increased, the height of the pillar is not proportion to it. After 900 Gauss magnetic induction, the pillars' size and height will decrease.

Discussion of Fluid Surface Tension

Surface tension is the other major factor that will affect the pillar generation. From experiments, we found that the height of the pillars, the shape of the pillar and the time for the pillars to lift up are also affected by the surface tension. To investigate the relationship between the MR fluid surface tension and pillar generation, iron powders were observed under applied magnetic field since they have no surface tension at all (Figure 5.25).



Figure 5.25 Iron powder on a free surface under the influence of a magnetic field.

In the previous part, we had shown the pillar height variation with different magnetic induction. For each strength of magnetic induction, we have tested twenty times.

We also observe that when the magnetic induction at low strength, the variation of the pillar height is quite large. The S.D. decreases when the magnetic induction increases. But this situation does not happen on the iron powder. The height of the iron powder pillars is uniform for the same magnetic induction strength.

In Figure 5.26, 5.27, 5.28, different strengths magnetic induction was applied to the iron powder. We observed that the height of iron powder pillars is higher than the MR fluid pillars. However the height difference was decreased when the strength of magnetic induction increases.

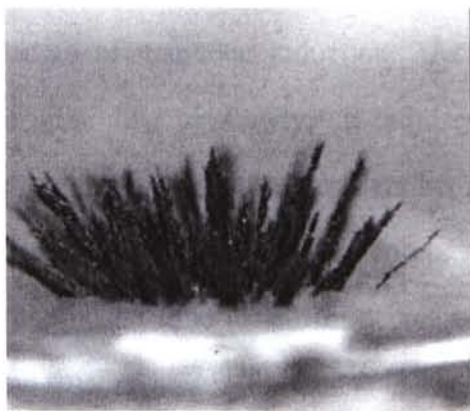


Figure 5.26 Iron powder pillars at 500 Gauss (3mm height)



Figure 5.27 Iron powder pillars at 1300 Gauss (2mm height)

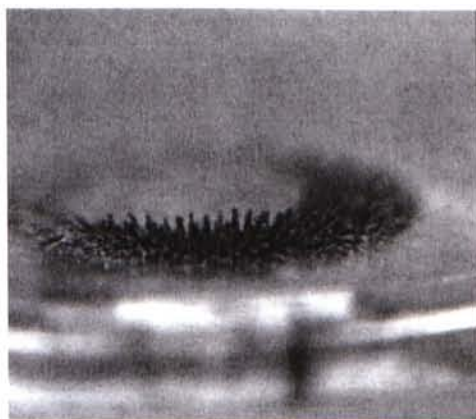


Figure 5.28 Iron powder pillars at 2100 Gauss (1.1mm height)

The time for pillars to lift up is also affected by the surface tension, especially for low strength of magnetic induction. At low magnetic induction strength, the flake-like pillar lifts up slowly. It requires about three seconds to completely lift up. However, the iron powder pillars lift up immediately when we applied the magnetic induction at the same strength. When we increase the magnetic induction strength, the time to lift up decreases. The effect of surface tension seems to become smaller.

CHAPTER SIX: APPLICATIONS

Introduction

The advantage of MEMS is to combine the mechanical and electrical parts into a small system. The controllability of the yield stress under magnetic field allows some electromechanical systems to be operated with increasing simplicity, quietness, rapid-response, and high reliability. By applying the MEMS technology, many macro systems can be reduced into micro systems. In this chapter, we will describe several possible systems that can apply MR fluid. These systems are micro brakes, micro clutches, and dampers for micro-robot systems. Moreover, a novel idea of MR fluid actuator is also proposed here.

MR Fluid Actuator

In chapter five, we have described and explained the MR fluid pillars in detail. From our experiments, we have found that the pillars can support small objects. If we compare to the weight of micro device, the pillars can lift up a heavy objects from the view of micro systems. We had carried out two different experiments to test the MR fluid pillars. In the first experiment, we have tried to lift up an object in static case. We apply the magnetic induction to the MR fluid suddenly, and then record the height of the objects that can be lifted. The second experiments is in dynamic case, the magnetic induction strength will change in the form of sinusoidal.

In the first experiment, we had used rubber as the object since its size can be changed easily. In Figure 6.1, a small rubber is placed on the top of the MR

fluid. The weight of the rubber is 0.27g. The surface that contacts the MR fluid is 10mm*5mm. The weight of the MR fluid is about 0.1g.

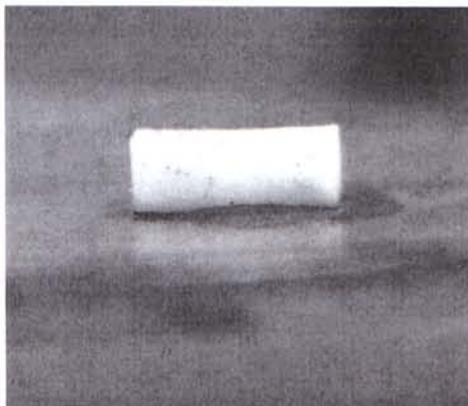


Figure 6.1 A rubber placed on the top of MR fluid

When we applied magnetic induction (2100 Gauss) to the MR fluid, the pillars were generated. The pillars push up the rubber about 1mm, as shown in Figure 6.2.

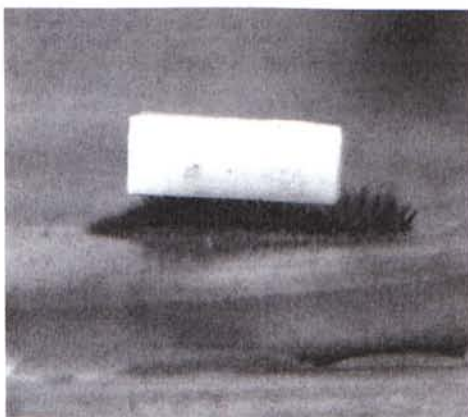


Figure 6.2 The rubber was lifted up about 1mm

Another rubber is placed on the top of MR fluid. The rubber is 0.52g and the surface contact to the MR fluid is 17mm*10mm. (Figure 6.3).

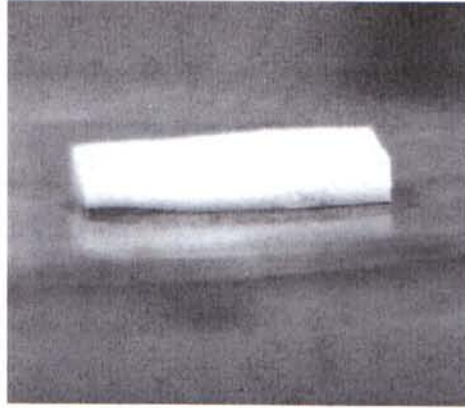


Figure 6.3 A rubber placed on the top of MR fluid

When the same strength magnetic induction (2100 Gauss) is applied, the rubber is lifted up again, (Figure 6.4) $\sim 0.9\text{mm}$

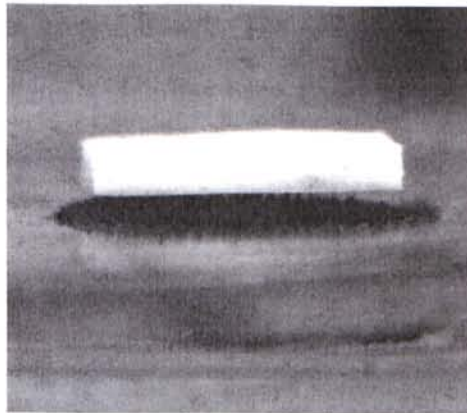


Figure 6.4 The rubber is lifted up about 0.9mm

If we compare the pillar height at 2100 Gauss (1.08mm), we found that the effect of putting some weight on top of pillar is not significant in the range of mass we have tested. Even though we change the surface of contact to $10\text{mm} \times 2\text{mm}$ by using the same rubber, the rubber can still be lifted up (Figure 6.5) with similar height. This points out that the pillars can generate enough force to push up an object that is at least 5 times of its weight. By apply this property, MR fluid can be used as linear actuators for micro systems.

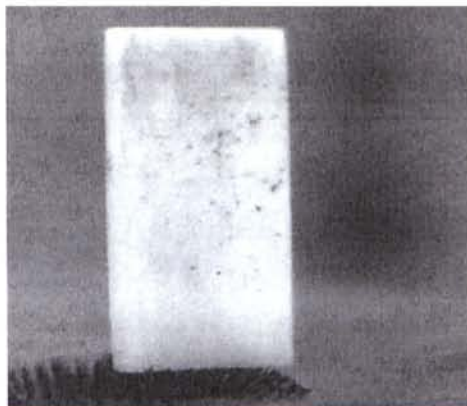


Figure 6.5 The rubber is lifted up about 0.9mm

The second experiment is the dynamic case. The whole experimental set up is shown in Figure 6.6. The magnet was put on a shaker as shown in Figure 6.7. The shaker can vibrate up and down. The MR fluid and rubber are placed on the top of a flat plastic plane which has been fixed in position. However, when the magnet vibrates, the plastic still has small vibration, because attractive force is present between the MR fluid and magnet. But the vibration of the plastic plane is very small, so we can neglect it.

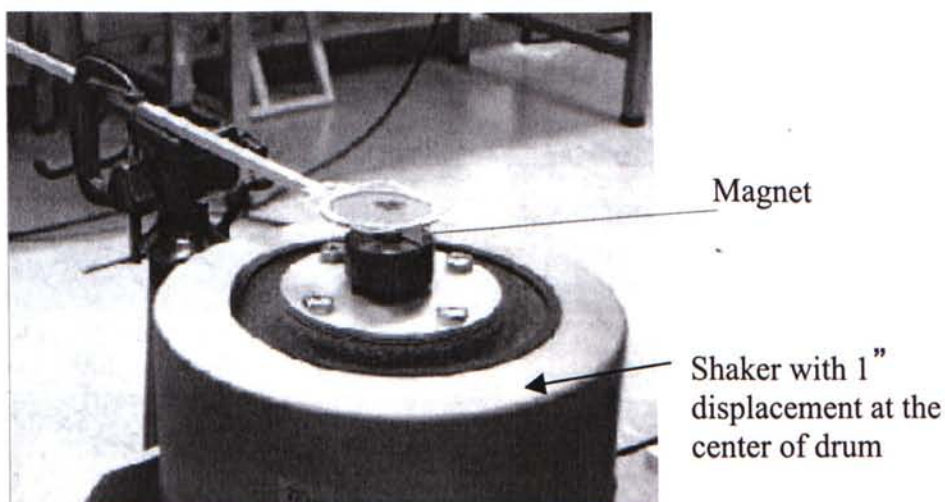


Figure 6.6 The experimental setup for the dynamic case

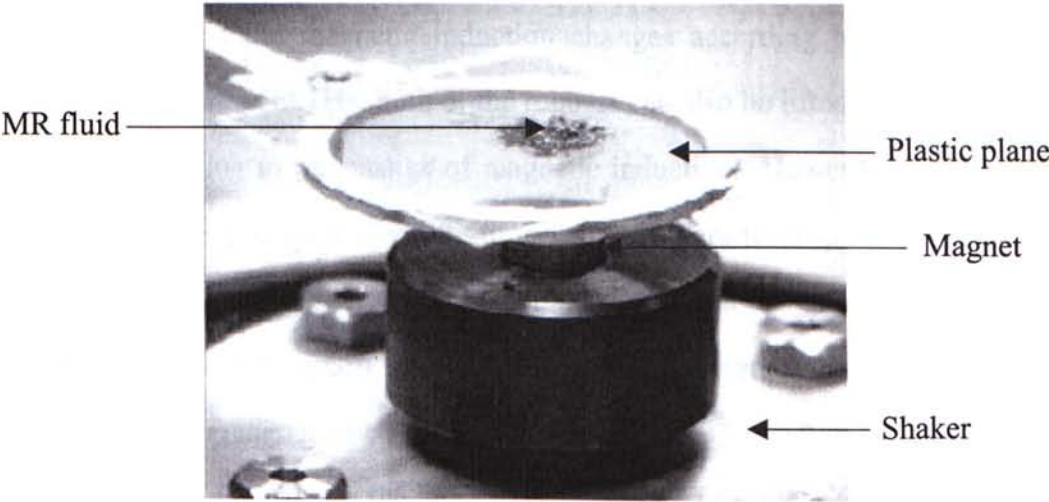


Figure 6.7 Close up of the experiment

By applying different vibration frequencies of the magnet to two different weight rubbers, six experiments were obtained. Figure 6.8-6.10 are the pictures of experiment 1 in one cycle. Figure 6.8 is the start of a cycle (trough) or the magnet is at the lowest position. Figure 6.9 is the middle of a cycle (crest) or the magnet is at the highest position. Figure 6.10 is the end of a cycle (trough) or the magnet goes back to the lowest position.

	Weight (g)	Vibration Frequency of the Magnet	Max B (Gauss)	Min B (Gauss)
Experiment 1	0.2	1Hz	1100	170
Experiment 2	0.52	1Hz	1100	170
Experiment 3	0.2	3Hz	800	300
Experiment 4	0.52	3Hz	800	300
Experiment 5	0.2	6Hz	800	450
Experiment 6	0.52	6Hz	800	450

Table 4. Experimental parameters of the dynamical test. The maximum magnetic induction (B) is lower for higher frequencies because the shaker amplitude is lower at the higher frequencies.

The aim of this set of experiments is to show the response time of the MR fluid pillars as the magnetic induction changes according to time. When the magnet is vibrated at 1Hz, both of the rubbers can also be lifted up by the MR fluid pillars according to the change of magnetic induction. However, the time for the pillars to lift up is more than the time for the pillars to drop down. Both of the rubbers have been lifted up with similar maximum height (0.5mm) when the magnet reach the highest point. Moreover, they can go back to the original position as the magnet reach the minimum point.

When we increase the vibration frequency of the magnet to 3Hz, both of the rubbers can also be lifted up. Due to the unequal distribution of the MR fluid and different magnetic induction under the rubbers, just a part of the rubbers can be lifted up. As we mentioned before, the rubber can be lifted up when the magnetic induction is high enough. The pillars just have enough force to lift up the rubbers. This problem seems to be more serious for the heavier rubber. However, both of the rubbers can also be lifted up with certain amount of height and go back to the original position in every cycle of vibration.

When the vibration frequency was increased to 6Hz, both of the rubbers were kept at certain height. It seemed that the MR fluid does not response to the change of magnetic induction. Since the pillars need some time to completely lift up and drop down, 6Hz is too high for the pillar to complete the movement.

From experiment 1-6, we can observe that the rubber can also be lifted up in the dynamic case. However the pillars also need some time to lift up and drop down. So as we want to use MR fluid as a meso actuator, we should consider two constraints. The first constraint is the magnetic induction strength should be large enough to lift up an object. The second constraint is the time dependency of pillar generation, which is speculated to be a complex function of fluid surface tension and magnetic particle alignment.

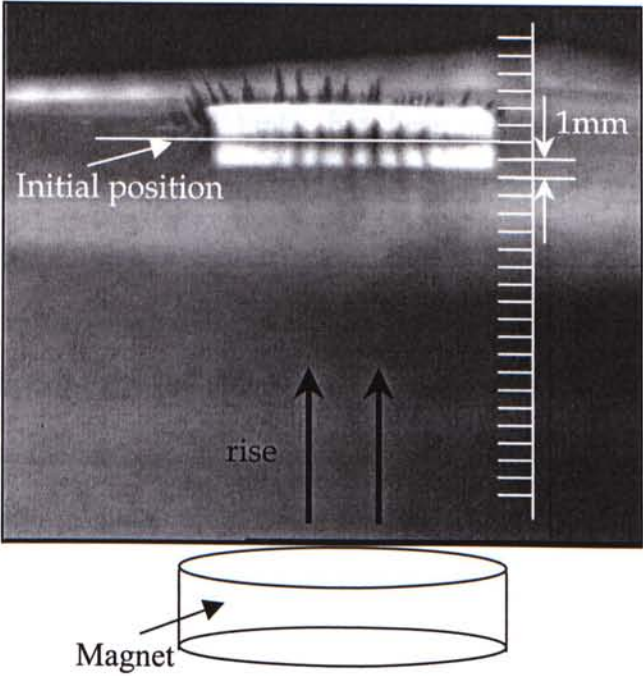


Figure 6.8 This is the starting state of the cycle (0s) with the magnet at the lowest point. The magnet is rising (the magnet is out of the picture). We have drawn the approximate position of the magnet. The white line under the rubber is the initial position of the rubber.

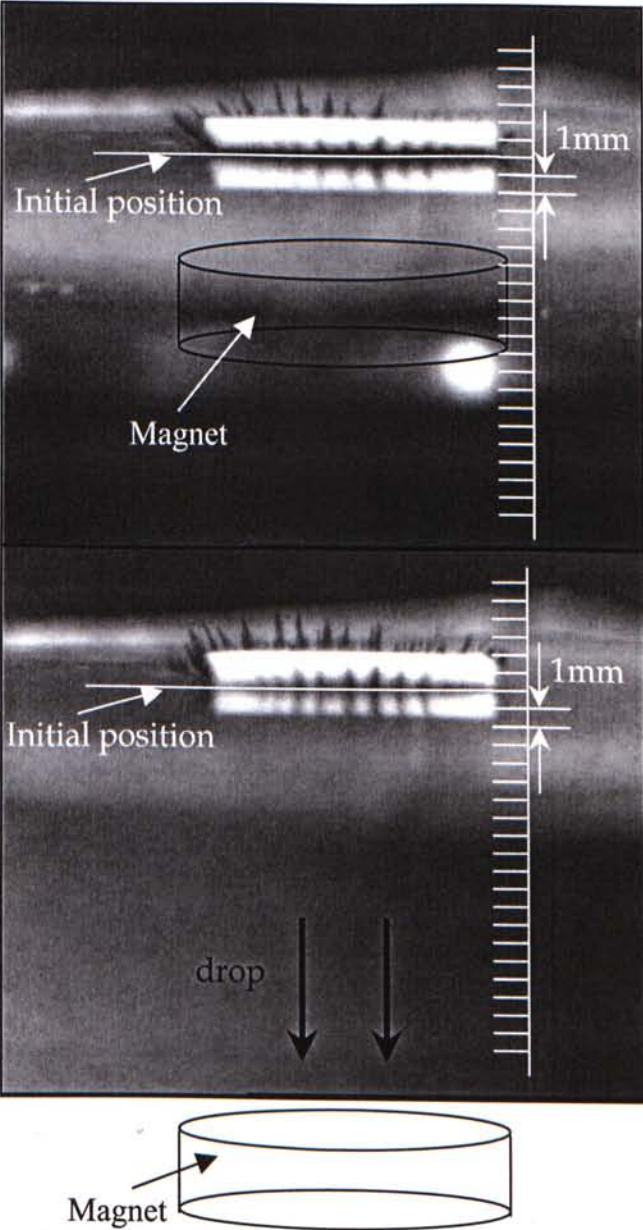


Figure 6.9 The magnet reach the highest position (0.5s). The rubber has been lifted up about 0.5mm. The white line under the rubber is the initial position of the rubber.

Figure 6.10 The magnet go back to the original position (1s). Moreover the rubber also goes back to the original position.

Micro Brake

MR fluid brake has been used in the programmable aerobic exercise machines as a controllable resistance device. Their simplicity and easy of control make them a cost-effective choice for the application of controllable exercise equipment and the precision tension control devices. The successfulness of the MR fluid brake in the commercial products proved that the idea of apply MR fluid to the brake system is possible. On the other hand, is it possible to apply the same idea to make micro brake systems? By surrounding the movable part with the MR fluid, we can decrease or evenly stop the movement or rotation parts of the micro system by changing the magnetic field strength. Due to the variable viscosity of MR fluid, electrical signal can be used to control the brake system that only requires few mechanical parts. We can apply the micro-MR fluid brake to the joints of micro-robot.

Micro Clutches

The idea of micro clutches is very similar to micro brakes. Both of them use the shear mode to operate. The principle of the micro clutches is to transfer the force or motion from one body to another body. By the idea of clutches, we can choose which part of the micro system is needed to transfer the force or movement.

Damper for Micro-Robot System

Micro-robot is one of the popular research topics currently. As we know, when robots move, vibration will be produced. How can we control this kind of vibration? The traditional dampers seem to be too complex to apply on micro robots. MR fluid is one of the suitable materials that may be used to make the dampers to control the vibration. We can control the viscosity by apply different strength of magnetic field. The MR fluid can be put into the damper that is

surrounded by the micro coil. If the MR fluid is integrated with the displacement sensor, it will become an active damper that can control the vibration at real time.

Besides the damper for micro robot, we may also use the MR fluid to protect the micro-robot under transportation. The micro robot is very easy to be damaged since the microstructure cannot absorb large vibration that may not damage macro devices. A possible solution is to put the micro robots or micro devices into the MR fluid vibration control system, then apply suitable magnetic field to the system. As a result, the micro devices can be transported with reduced effects from environmental vibrations.

CHAPTER SEVEN:

CONCLUSION

From the preliminary theoretical analysis and experiments, we have determined that many limitations will inhibit the application of MR fluids in micron-sized systems currently. However, commercially available MR fluids can be used in submillimeter sized MEMS devices if considerations to minimal volume, magnetic field generation method and screen printing technique are given. We have also found that it is possible to generate and control MR fluid pillars on free fluid surfaces by varying the magnetic field surrounding the fluid. The Surface tension of MR fluid will affect their behaviour at micro scale, especially the pillar generation. By using the power of MR fluid pillar, a novel idea for meso actuation was introduced.

APPENDIX

Quantity	Symbol	SI	emu
Magnetic field	H	A/m	Oe (oersted)
Magnetic induction	B	T (tesla)	G (gauss)
Magnetic flux	ϕ	Wb (weber)	Maxwell
Coercive force	H _c	A/m	Oe
Magnetic permeability	μ	H/m	
Remanence	Br	T	G

$$1 \text{ Oe} = 79.6 \text{ A/m};$$

$$1 \text{ G} = 10^{-4} \text{ T};$$

$$1 \text{ Maxwell} = 10^{-8} \text{ Wb};$$

$$\text{Magnetic permeability of free space } \mu_0 = 4\pi \cdot 10^{-7} \text{ H/m};$$

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